Neutron-Antineutron Oscillation Experiments: What Have We Learned at the Workshop?

W. M. Snow
Indiana University/CEEM
Project X Workshop

Why $\Delta B=2$? (theory/phenomenology)

Neutron-antineutron oscillations in nuclei:theory and experiment

Free neutron oscillations: experimental requirements @Project X

Thanks to co-conveners: Chris Quigg (FNAL), Albert Young (NC State)

Neutron-Antineutron Oscillations: Speaker List (from Germany, Georgia, India, Japan, US)

Speaker	Subject
R. Mohapathra, Maryland	theory/phenomonology
M. Snow, Indiana	various
G. Greene, ORNL/Tennessee	R&D needs
I. Gogoladze, Bartol/Delaware	theory/phenomonology
M. Chen, Irvine	leptogenesis
K. Babu, Oklahoma State	theory/phenomonology
M. Stavenga, FNAL	theory
M. Buchoff, LLNL	theory/lattice
E. Kearns, Boston	experiment/nnbar in nuclei
A. Vainshtein, Minnesota	theory/nnbar in nuclei
Y. Kamyshkov, Tennessee	experiment options
R. Tayloe, Indiana	detectors
K. Ganezer, CSUDH	nnbar in nuclei
D. Dubbers, Heidelberg	ILL experiment
T. Gabriel, ORNL/Tennessee	SNS 1MW target
G. Muhrer, LANL	1MW target/moderator design
H. Shimizu, Nagoya	neutron supermirror optics
C-Y Liu, Indiana (also for D. Baxter, Indiana)	moderator experiments/simulations
S. Banerjee, Tata Institute	detectors

Neutron-Antineutron Oscillations: Formalism

$\alpha \neq 0$ allows oscillations

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$ n-nbar state vector

$$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$ Hamiltonian of n-nbar system

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Note :

- α real (assuming T)
- $m_n = m_{\bar{n}}$ (assuming CPT)
- $U_n \neq U_{\bar{n}}$ in matter and in external B [$\mu(\bar{n}) = -\mu(n)$ from CPT]

Neutron-Antineutron transition probability

For $H = \begin{pmatrix} E+V & \alpha \\ \alpha & E-V \end{pmatrix}$ $\qquad P_{n\to\bar{n}}(t) = \dfrac{\alpha^2}{\alpha^2+V^2} \times \sin^2\left[\dfrac{\sqrt{\alpha^2+V^2}}{\hbar}t\right]$

where V is the potential difference for neutron and anti-neutron.

Present limit on $\alpha \leq 10^{-23} eV$

Contributions to V:

<Vmatter>~100 neV, proportional to density

<Vmag>=μB, ~60 neV/Tesla; B~10nT-> Vmag~10^{-15} eV

<Vmatter> , <Vmag> both >>α

For $\left[\dfrac{\sqrt{\alpha^2+V^2}}{\hbar}t\right] << 1$ ("quasifree condition") $\qquad P_{n\to\bar{n}} = \left(\dfrac{\alpha}{\hbar}\times t\right)^2 = \left(\dfrac{t}{\tau_{n\bar{n}}}\right)^2$

Figure of merit= NT^2 N=#neutrons, T="quasifree" observation time

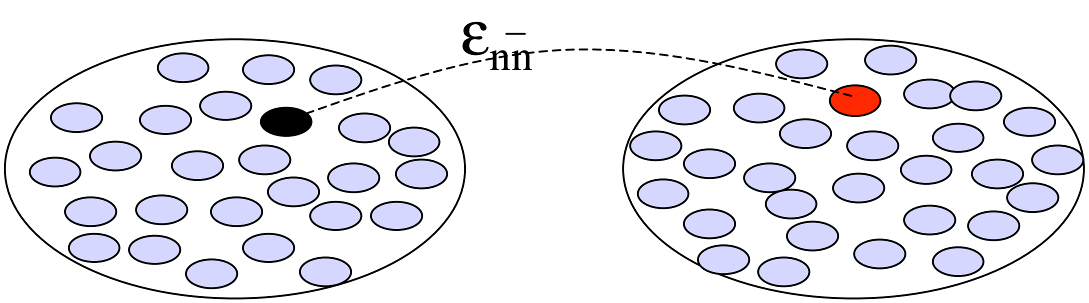
How to Search for N-Nbar Oscillations

Figure of merit for probability: $$NT^2$$
N=total # of free neutrons observed
T= observation time per neutron while in "quasifree" condition

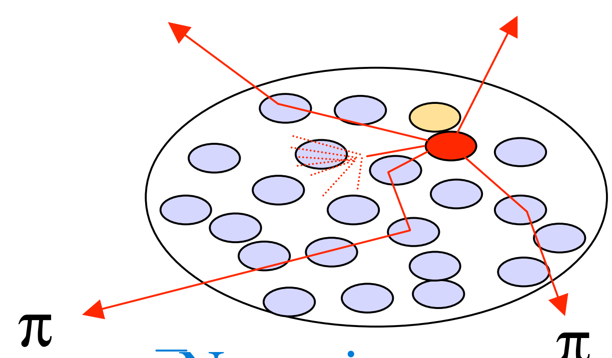
When neutrons are in matter or in nucleus, n-nbar potential difference is large->quasifree observation time is short

B field must be suppressed to maintain quasifree condition due to opposite magnetic moments for neutron and antineutron

(1) n-nbar transitions in nuclei in underground detectors
(2) Cold and Ultracold neutrons



Nucleus $A \rightarrow A^* + \bar{n}$



$\bar{n}N \rightarrow$ pions

Why is it important to search for NNbar ?

- Many reasons to believe that **baryon number (B) is not a good symmetry of nature :**

Sphalerons in SM , GUTs, origin of matter etc.

- If B is violated, important to determine the selection rules: B=1 (p-decay) or B=2 (NNbar) ?

i) What is the scale at which B- symmetry is broken ?

NNbar → lower scale physics than usual p-decay

ii) NNbar oscillation intimately connected to neutrino mass physics when combined with quark-lepton unification

Questions for N-N-bar oscillation

- Are there decent (predictive?)theories explaining small neutrino masses which give observable N-N-bar oscillation ?
- Implications of observable N-N-bar for cosmology i.e. does it affect conventional explanations of origin of matter/can it explain itself ?
- Two examples of models for NNbar:

(i) **TeV scale Seesaw +Quark-Lepton unif.**

(ii) **SO(10) GUT scale seesaw+TeV sextets**

New Particles at LHC:

Color sextet scalars Δ_{qq}

- TeVColor sextets are an inherent part of both models ; Can be searched at LHC:

(I) **Single production**: $\boxed{ud \longrightarrow \Delta_{ud} \longrightarrow tj}$

xsection calculated in **(RNM, Okada, Yu' 07;)** resonance peaks above SM background- decay to tj;

- **Important LHC signature:** $\sigma(tt) > \sigma(\bar{t}\bar{t})$

(II) **Drell-Yan pair production** $\boxed{q\bar{q} \to G \to \Delta_{ud}\bar{\Delta}_{ud}}$

- Leads to $tjtj$ final states: **LHC reach < TeV**

(Chen, Rentala, Wang; Berger, Cao, Chen, Shaughnessy, Zhang' 10; Han, Lewis' 09)

Origin of matter and neutron oscillation

- Current scenarios:

(i) Leptogenesis; Related to seesaw; but hard to test !

(ii) Electroweak baryogenesis :

M_{higgs} <127 GeV; $m_{\tilde{t}} \leq 120 GeV$ (puts MSSM under tension)

- New scenarios: (Babu's talk)

$\left.\begin{array}{l}\text{(iii) Post sphaleron Baryogenesis} \\ \text{(iv) GUT baryogenesis}\end{array}\right\}$ both connected to NNbar osc.

- Non-observation of NNbar upto 10^{11} sec.will rule out simple models for PSB as well as the particular SO(10) model.

Summary and Conclusions

Post–sphaleron baryogenesis predicts observable $n - \overline{n}$ oscillations

Colored scalars at TeV scale should be accessible to LHC

New GUT scale $(B - L)$–genesis proposed which is sphaleron–proof

Both models predict

$$\tau(n - \overline{n}) \sim (10^9 - 10^{11}) \text{ sec}$$

$n - \overline{n}$ oscillation experiments can probe a class of theories which explains the origin of matter in the universe

Conclusions

- origin of matter: one of the great mysteries in particle physics and cosmology
- leptogenesis: an appealing baryogenesis mechanism connected to neutrino physics
- various leptogenesis mechanisms:
  - standard leptogenesis: gravitino problem, incompatible with SUSY
  - resonance leptogenesis
  - Dirac leptogenesis

- While there is no model-independent way to test leptogenesis, searches at neutrino experiments (leptonic CPV, neutrino-less double beta decay) can provide supports for/distinguish among the mechanisms
- neutron-antineutron oscillation: complementarity test
  - if observed $\Rightarrow$ low scale leptogenesis scenarios preferred

B violation theory: What did we learn?

- R. Mohapathra/K. Babu/I. Gogoladze: models exist which give nnbar oscillations within range of improved experiments. Such models tend to possess rather specific structures and also produce signatures at LHC

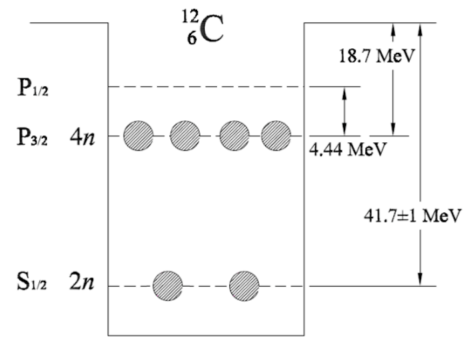
- K. Babu: “post-sphaeleron” baryogenesis possibility (which can only be $\Delta B=2$) is NOT ruled out experimentally. Present models tend to make observable LHC predictions.

- K. Babu/R. Mohapathra: Effective field theory analysis of all d=9, $\Delta B=2$ operators in progress (not done before!), might make possible more model-independent statements.

- M. Chen: "standard" leptogenesis has some problems already! "Resonant" leptogenesis and Dirac leptogenesis also possible (latter since sphaelerons only couple to left-handed components). NNbar possibility is complementary to leptogenesis. Leptogenesis is very difficult to confirm experimentally.

Suppression of n→nbar in intranuclear transitions

Neutrons inside nuclei are "free" for the time: $\Delta t \sim \dfrac{\hbar}{E_{binding}} \sim \dfrac{\hbar}{30MeV} \sim 4.5\times 10^{-22}s$



each oscillating with "free" probability $= \left(\dfrac{\Delta t}{\tau_{n\bar{n}}}\right)^2$

and "experiencing free condition" $N = \dfrac{1}{\Delta t}$ times per second.

Transition probability per second: $P_A \doteq \dfrac{1}{\tau_A} = \left(\dfrac{\Delta t}{\tau_{n\bar{n}}}\right)^2 \times \left(\dfrac{1}{\Delta t}\right)$

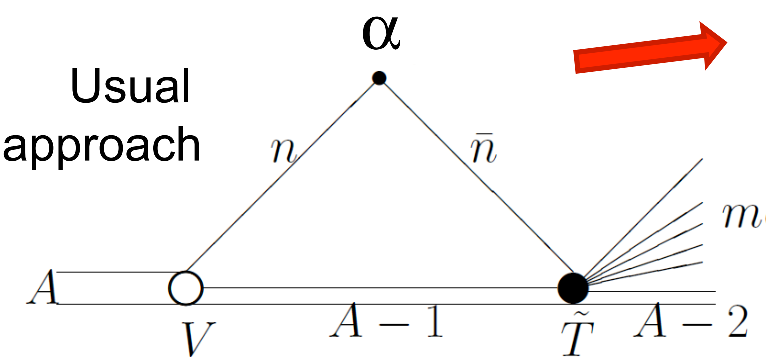
Intranuclear transition (exponential) lifetime: $\boxed{\tau_{\mathrm{A}} = \dfrac{\tau_{n\bar{n}}^2}{\Delta t} = R \leftrightarrow \tau_{n\bar{n}}^2}$

where $\mathrm{R} \sim \dfrac{1}{\Delta \mathrm{t}} \sim 4.5 \leftrightarrow 10^{22} s^{-1}$ is "nuclear suppression factor"

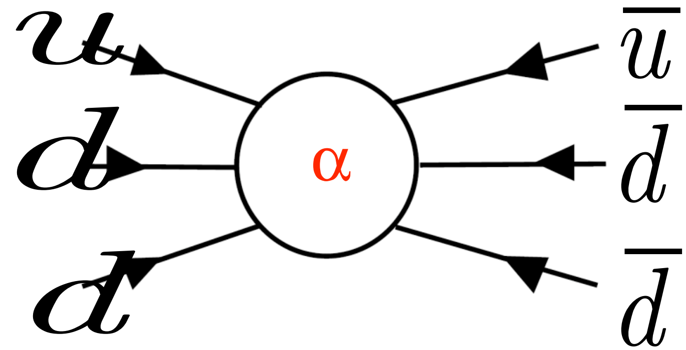
Actual nuclear theory suppression calculations for $^{16}O,^{2}D,^{56}Fe,^{40}Ar$ by C. Dover et al; W.Alberico et al; B.Kopeliovich and J. Hufner, and most recently by Friedman and Gal (2008) corrected this rough estimate within a factor of 2

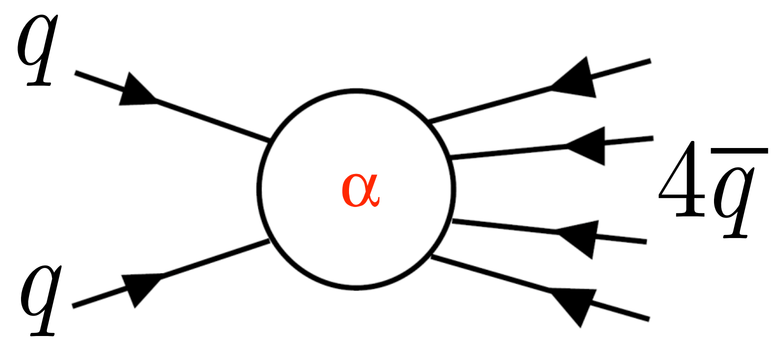
Theoretical nuclear NNbar suppression model is incomplete

Usual approach

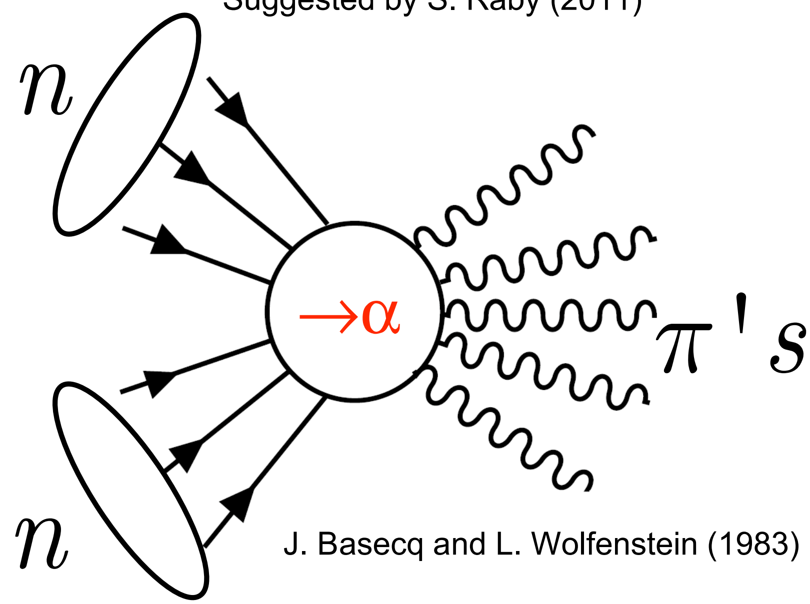


All these processes →
include the same amplitude α
and result in the same
indistinguishable final state
(of ~ 5 πs)





Suggested by S. Raby (2011)



J. Basecq and L. Wolfenstein (1983)

Existing intranuclear NNbar limits need to be re-evaluated

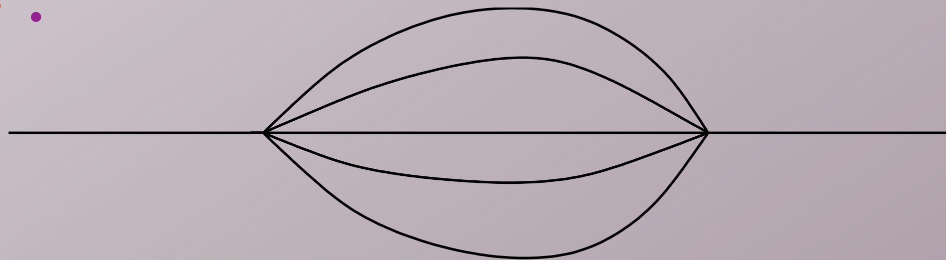
Estimate

Let us try to use some kind of duality to find a relation between the free $n \leftrightarrow \bar{n}$ oscillation and nuclear stability.

$$\langle \bar{n} | c^*_{\mathcal{O}} \mathcal{O}^\dagger | n \rangle = \epsilon \, \bar{u}^c_{\bar{n}} \gamma_5 u_n \qquad |\epsilon| = \frac{\hbar}{\tau_{n\bar{n}}}$$

where $\mathcal{O}^\dagger$ decreases $B, \;\; \Delta B = 2$.

Operator product expansion

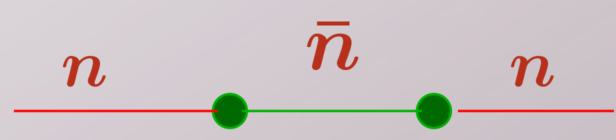


$$\int d^4x \, \mathrm{e}^{iqx} T\{\mathcal{O}(x)\mathcal{O}^\dagger(0)\} = c_q \, \bar{q} q + \ldots$$

The average over a nucleus A gives its lifetime τ_A

$$2|c_{\mathcal{O}}|^2 \mathrm{Im} \int d^4x \langle A | T\{\mathcal{O}(x)\mathcal{O}^\dagger(0)\} | A \rangle = \frac{\hbar}{\tau_A}$$

The average over neutron state



$$|c_{\mathcal{O}}|^2 \int d^4x\, \mathrm{e}^{iqx} \langle n|T\{\mathcal{O}(x)\mathcal{O}^\dagger(0)\}|n\rangle \sim \frac{|\epsilon|^2}{\Delta}$$

where Eucledian $q \sim \Delta$ is a relevant hadronic duality scale.

Taking $\langle A|\bar{q}q|A\rangle \sim A\,\langle n|\bar{q}q|n\rangle$ for the leading OPE term we get

$$\tau_A = R\,\tau^2_{n\bar{n}}\,,_n \quad R = \frac{\Delta}{A\hbar}$$

For ^{16}O and an educated guess for $\Delta = 0.5\ \mathrm{GeV}$

$$R = 4.7 \times 10^{22}\ s^{-1}$$

what is close to the result obtained by Friedman, Gal (2008).

The inclusive approach does include all the mechisms.

PROTON DECAY

- Proton is a topological non-trivial configuration of the pion field (Skyrmion)
- Decay of the proton is protected by topology
- Hybrid Skyrmion/bag model decay possible but exponentially suppressed due to tunneling (instanton)

DISCUSSION

- We calculated hadronic matrix elements including non-perturbative QCD effects resulting in suppression.
- This suppression can be sizeable.
- Drawback not a very stable calculation due to bag size.

Where Lattice Can Help

- Is BSM running non-perturbative?
  - Model-dependent (assume pert. models for now)
- Is QCD running non-perturbative?
  - Should be checked (pert. running reasonable)
- What is neutron-antineutron matrix element?
  - Inherently non-perturbative question
- What is effect in nuclei?
  - Very interesting, VERY hard question

Future Outlook

Currently in progress:

- Independent analysis checks
- L = 20, 390 MeV pions
- L = 32, 240 MeV pions

Feasible in the next year or two:

- Physical Point Calculation
- Chiral Fermion Calculation

NNbar suppression factor in nuclei: theory developments

A. Vainshtein: operator product expansion calculation in progress (with B. Kopeliovich) will implicitly include all processes and give independent estimate of size and error of Gal calculation.

M. Buchoff: lattice calculation of nnbar transition matrix element in progress, special structure of nnbar operator makes it possible, should make possible quantitative connection between nnbar limit and energy scale

M. Stavenga: Skyrme calculation of extra suppression of B violation from chiral dynamics?

ALSO (Vainshtein): $\Delta B=2$ in nuclei can also come from "di-proton decay", How does this affect limits form nnbar in nuclei?

Vacuum N-Nbar transformation from bound neutrons:

Best result so far from Super-K in Oxygen-16

$$\boxed{\tau_{^{16}O} > 1.89 \leftrightarrow 10^{32}\, yr \quad (90\%\ \text{CL})}$$

$\Re$ 24 observed candidates;
24.1 exp. background

$$\boxed{\tau_{nucl} = R \times \tau^2_{n\bar{n}\ \text{free}}}$$

$$\text{if } R_{^{16}O} = 5 \cdot 10^{22} s^{-1} \quad \text{(from Friedman and Gal 2008)}$$

$$\Rightarrow \tau(\text{from bound}) > 3.5 \times 10^{8} s \quad \text{or} \quad \alpha < 2 \times 10^{-24} eV$$

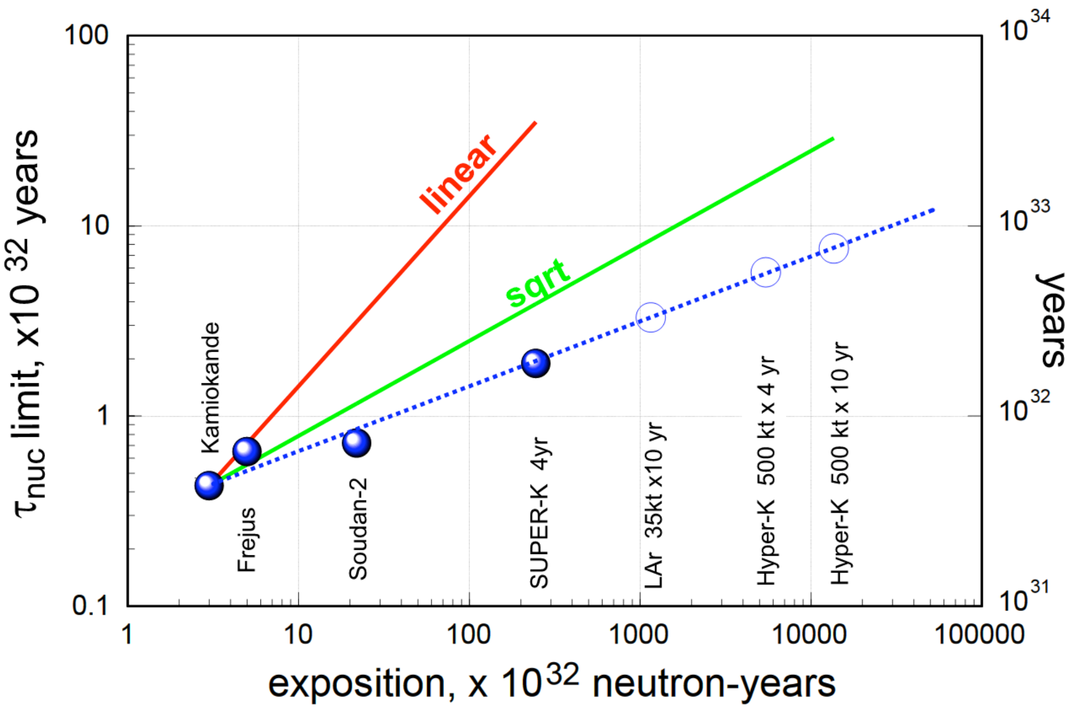
↔16 times higher than sensitivity of ILL expt.

ILL limit (1994) for free neutrons: $\tau_{n\bar{n}} > 0.86 \times 10^{8} s$

Bound neutron N-Nbar search experiments

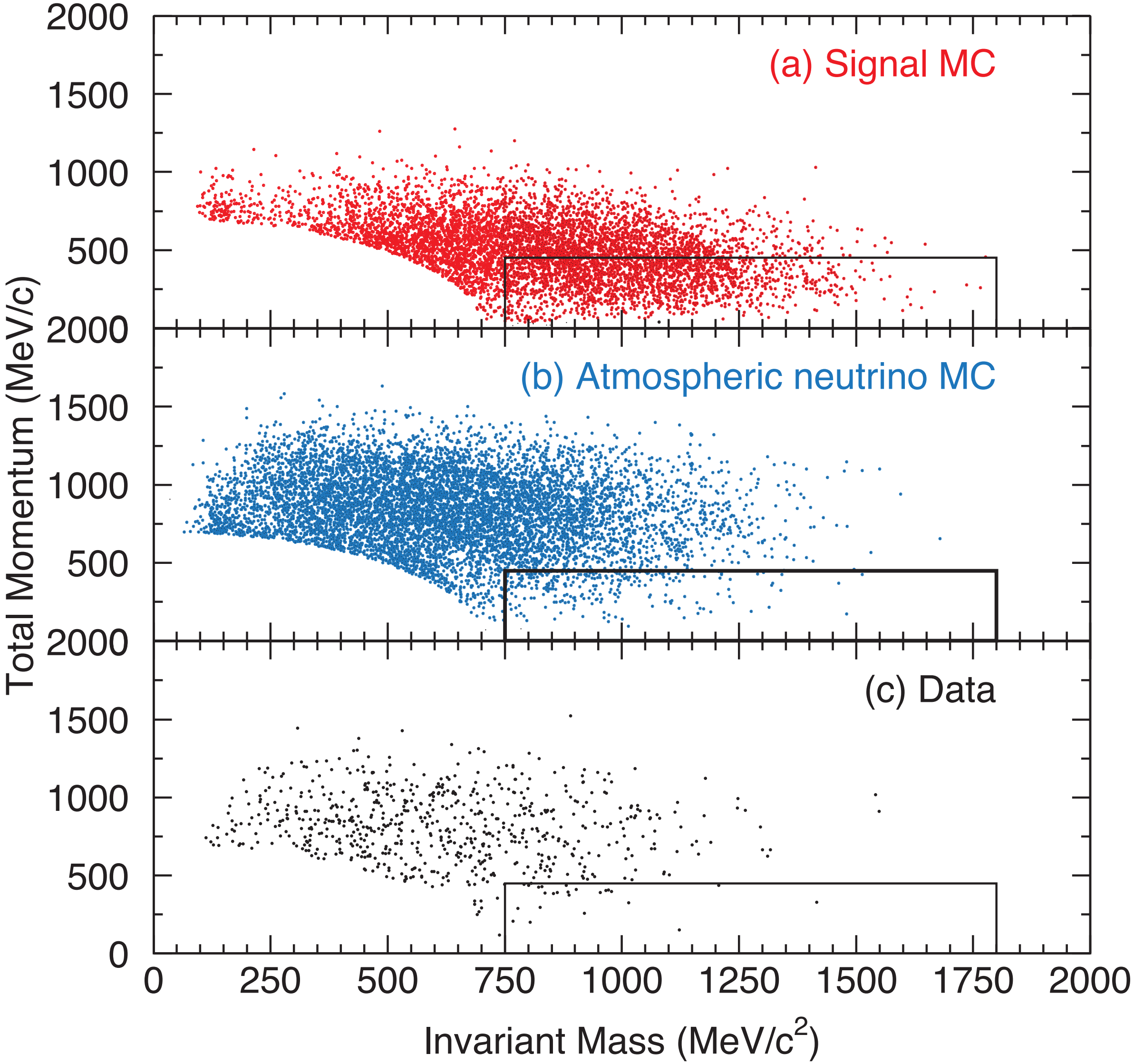
Experiment	Year	A	n·year (10^{32})	Det. eff.	Candid.	Bkgr.	τ_{nucl}, yr (90% CL)
Kamiokande	1986	O	3.0	33%	0	0.9/yr	$>0.43\times10^{32}$
Frejus	1990	Fe	5.0	30%	0	4	$>0.65\times10^{32}$
Soudan-2	2002	Fe	21.9	18%	5	4.5	$>0.72\times10^{32}$
SNO *	2010	D	0.54	41%	2	4.75	$>0.301\times10^{32}$
Super-K	2011	O	245	12.1%	24	24.1	$>1.89\times10^{32}$

* Preliminary



- From Kamiokande to Super-K atmospheric ν background is about the same ~ 2.5 /kt/yr.
- Large D_2O, Fe, H_2O detectors are dominated by backgrounds; LAr detectors are unexplored
- Observed improvement is weaker than SQRT due to irreducible background and uncertainties of efficiency and background.
- Still possible to improve a limit but impossible to claim a discovery.

Super-Kamiokande Result



12 % detection efficiency
sys. uncertainty 23%
(mostly intranuclear scattering)

24.1 background events
ν osc. effects are included
sys. uncertainty 24%
(mostly flux, cross sections)

24 candidates

$$T_{bound} > 1.89 \times 10^{32} \text{ years}$$

$$\tau_{free} = \sqrt{\frac{T_{bound}}{1 \times 10^{23} \text{ s}^{-1}}} = 2.4 \times 10^{8} \text{ s}$$

Liquid Argon TPC

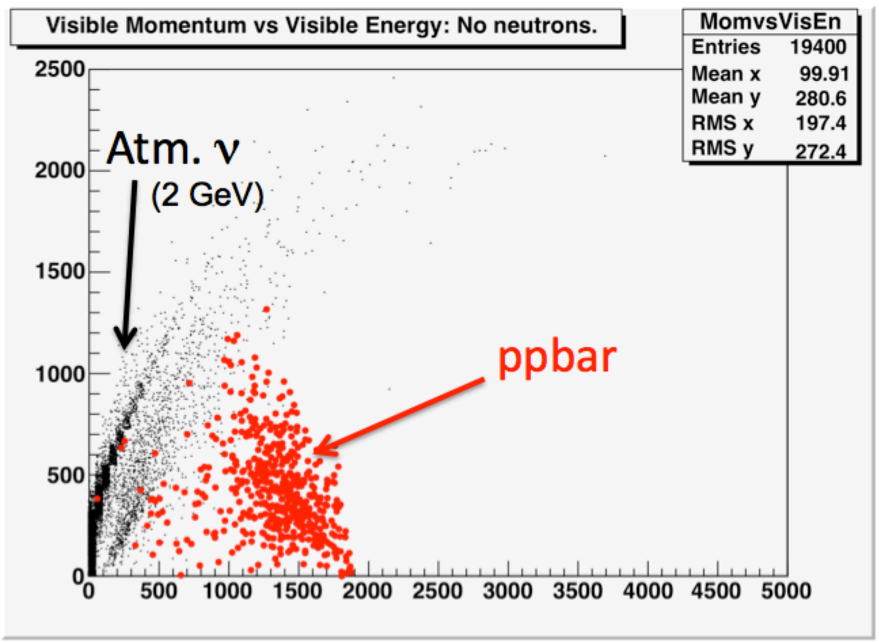
Compared to Iron Calorimeters:

- can do better than requiring n_{ch} >= 4

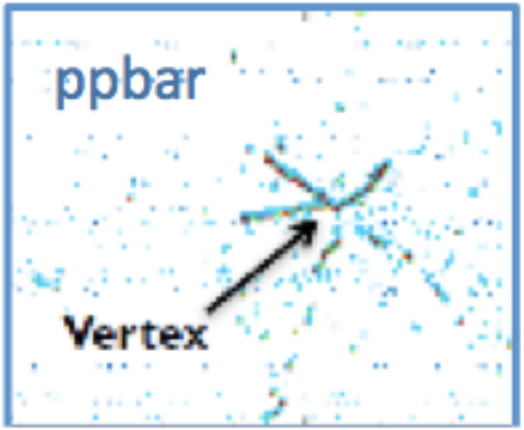
Compared to WC

- can resolve recoil proton, charged current lepton

Potentially big gains in efficiency and BG rejection!



Good discrimination at least at truth level.



G. Karagiorgi, LBNE-docdb-5645

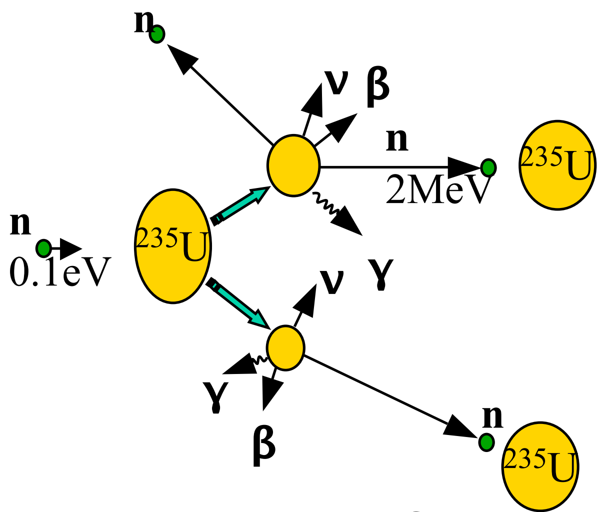
Observations

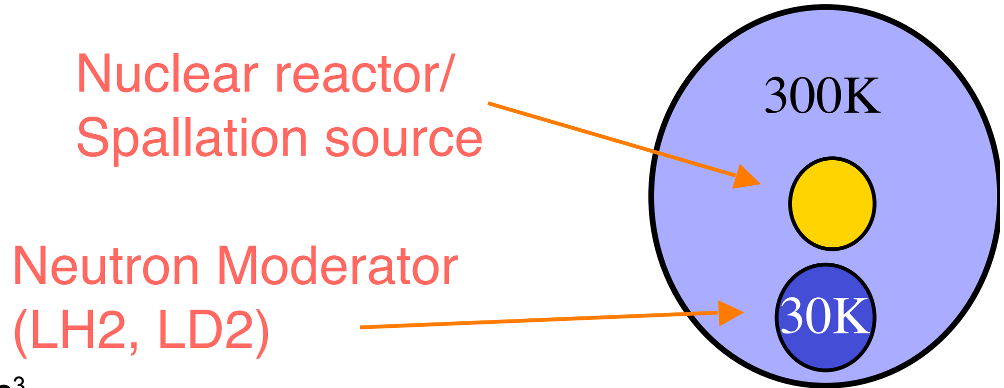
- Proton decay detectors have a long history of studying nnbar. Usual qualities apply:
  large mass, high efficiency, low background

- Analyses have been fairly crude so far. No modern MVA techniques. High background rate in water cherenkov is daunting.

- LAr TPC, even one as small as LBNE/10 kton should do very well. Let's study!

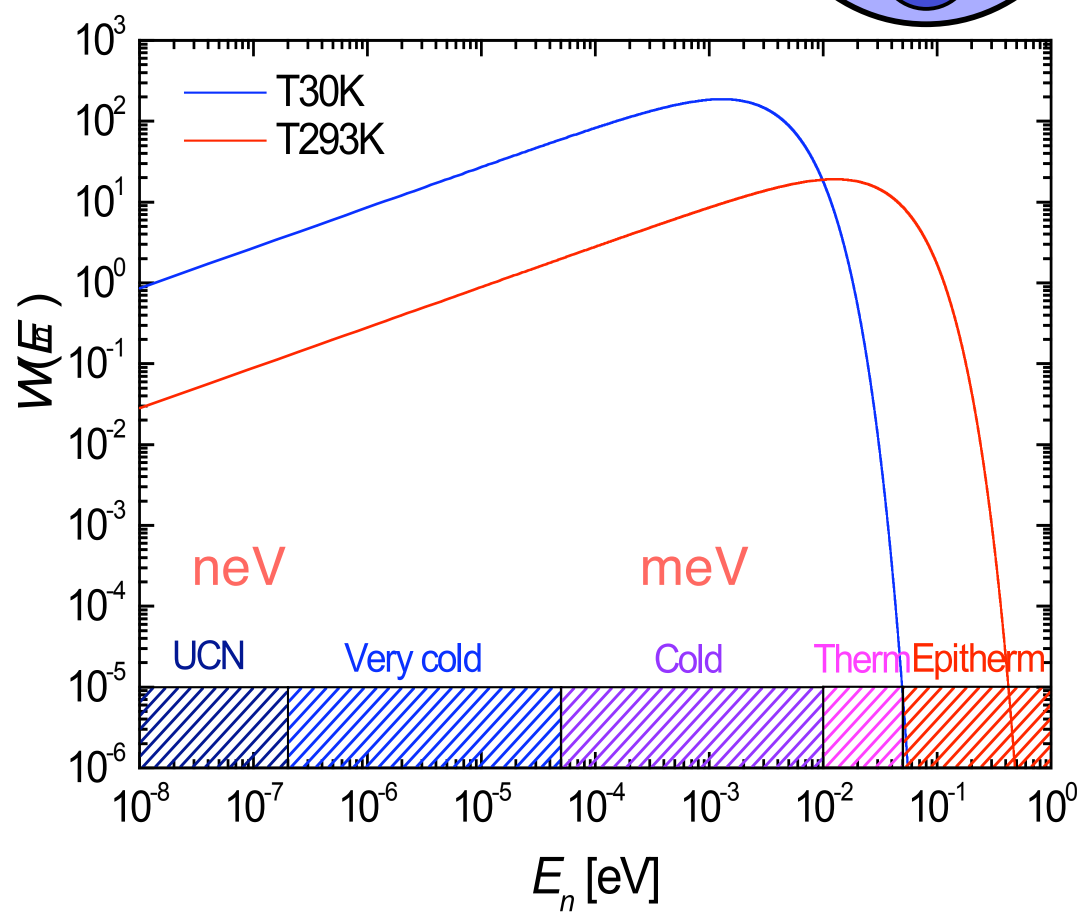
“Slow” Neutrons: MeV to neV



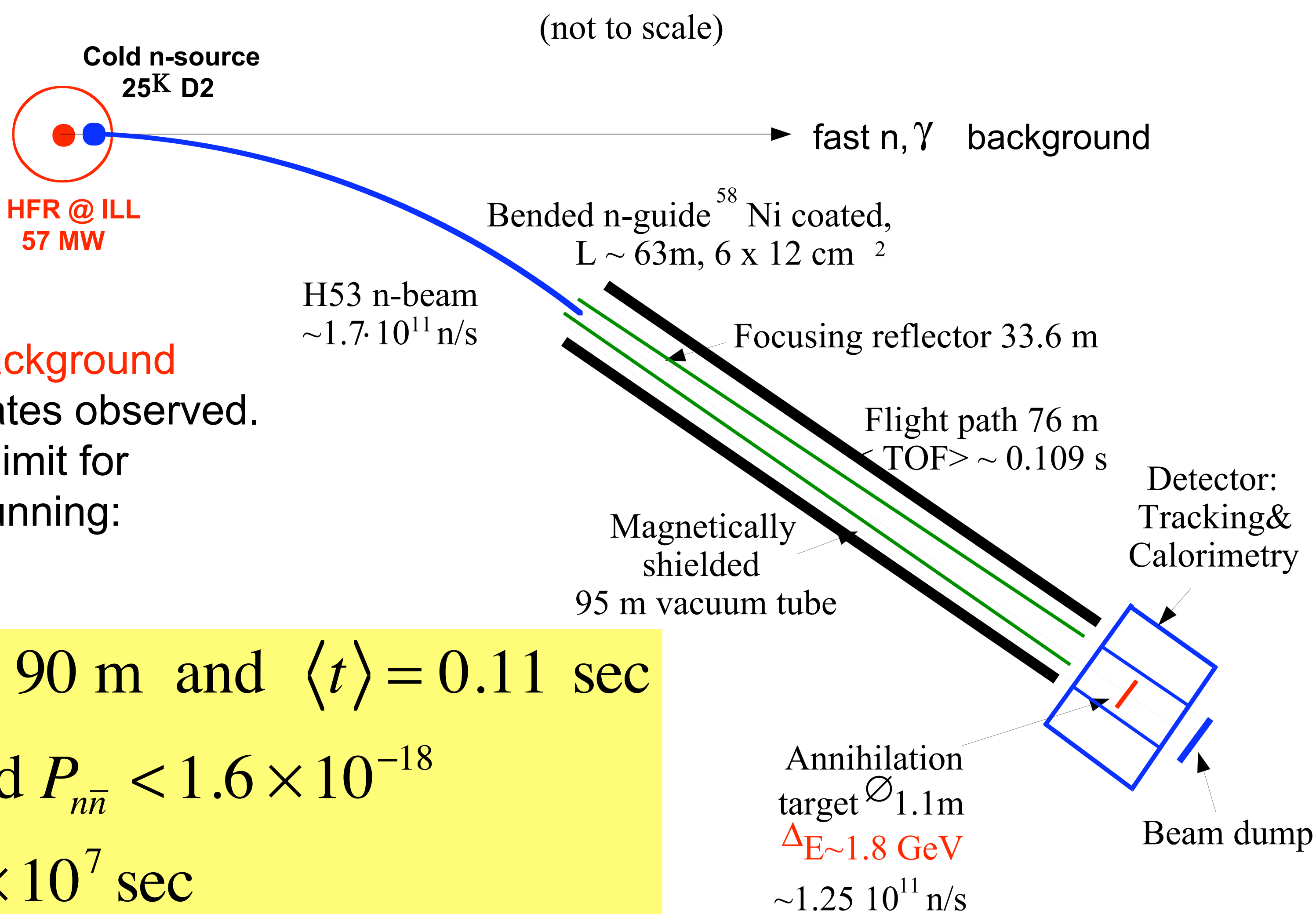


~MeV neutrons from fission or spallation, thermalized in ~ 20 collisions in ~ 100 μs

T (K)	E (meV)	λ (A)	v (m/sec)
300	25	1.6	2200
20	2	6.4	550



N-Nbar search at ILL (Heidelberg-ILL-Padova-Pavia)



No GeV background
No candidates observed.
Measured limit for
a year of running:

$$\text{with L} \sim 90 \text{ m and } \langle t \rangle = 0.11 \text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$

$$\tau > 8.6 \times 10^{7} \text{ sec}$$

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

Quasifree Condition: B Shielding and Vacuum

$\mu B t \ll \hbar$ ILL achieved |B|<10 nT over 1m diameter, 80 m beam,one layer 1mm shield in SS vacuum tank, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991). For new experiment need |B|<~1 nT

If nnbar candidate signal seen, easy to “turn it off” by increasing B

$V_{opt} t \ll \hbar$:

Need vacuum to eliminate neutron-antineutron optical potential difference.

$P<10^{-5}$ Pa is good enough, much less stringent than LIGO

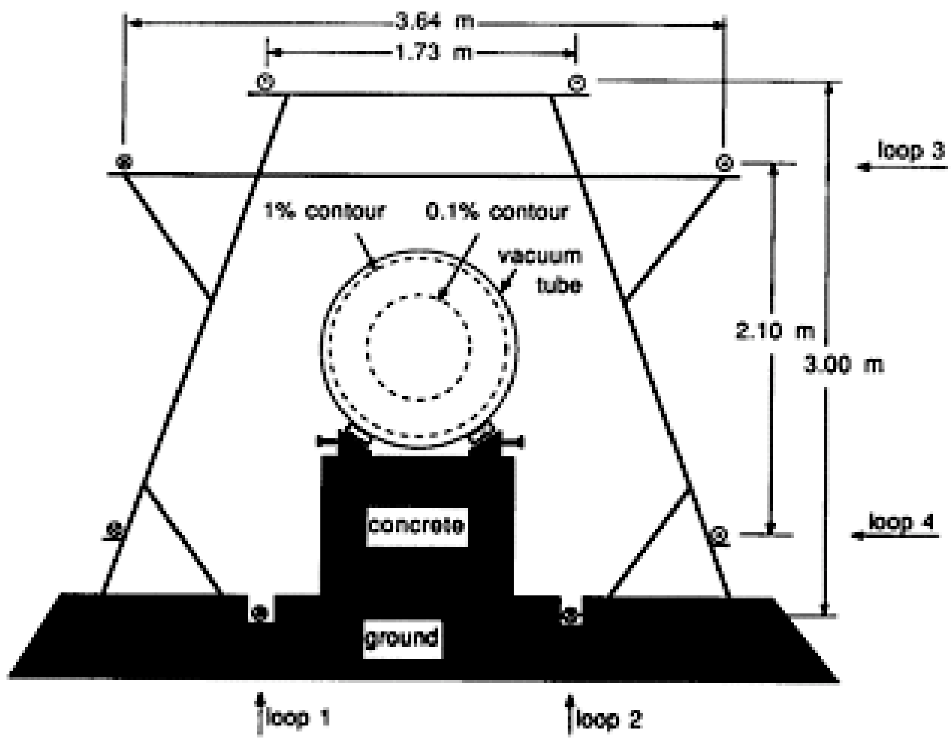
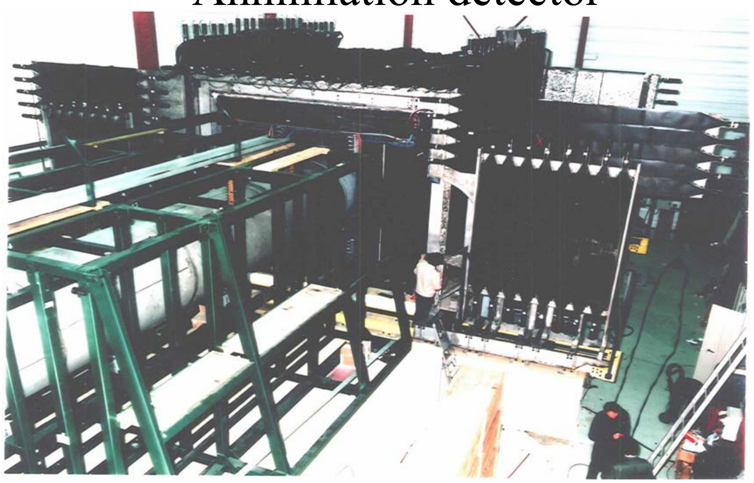


Fig. 10. The transverse field compensation system. Loops 1 and 2 are under 49 A current and compensate the horizontal field component; loops 3 and 4 are under 120 A current and compensate the vertical field component.

2. ILL n-nbar beam line

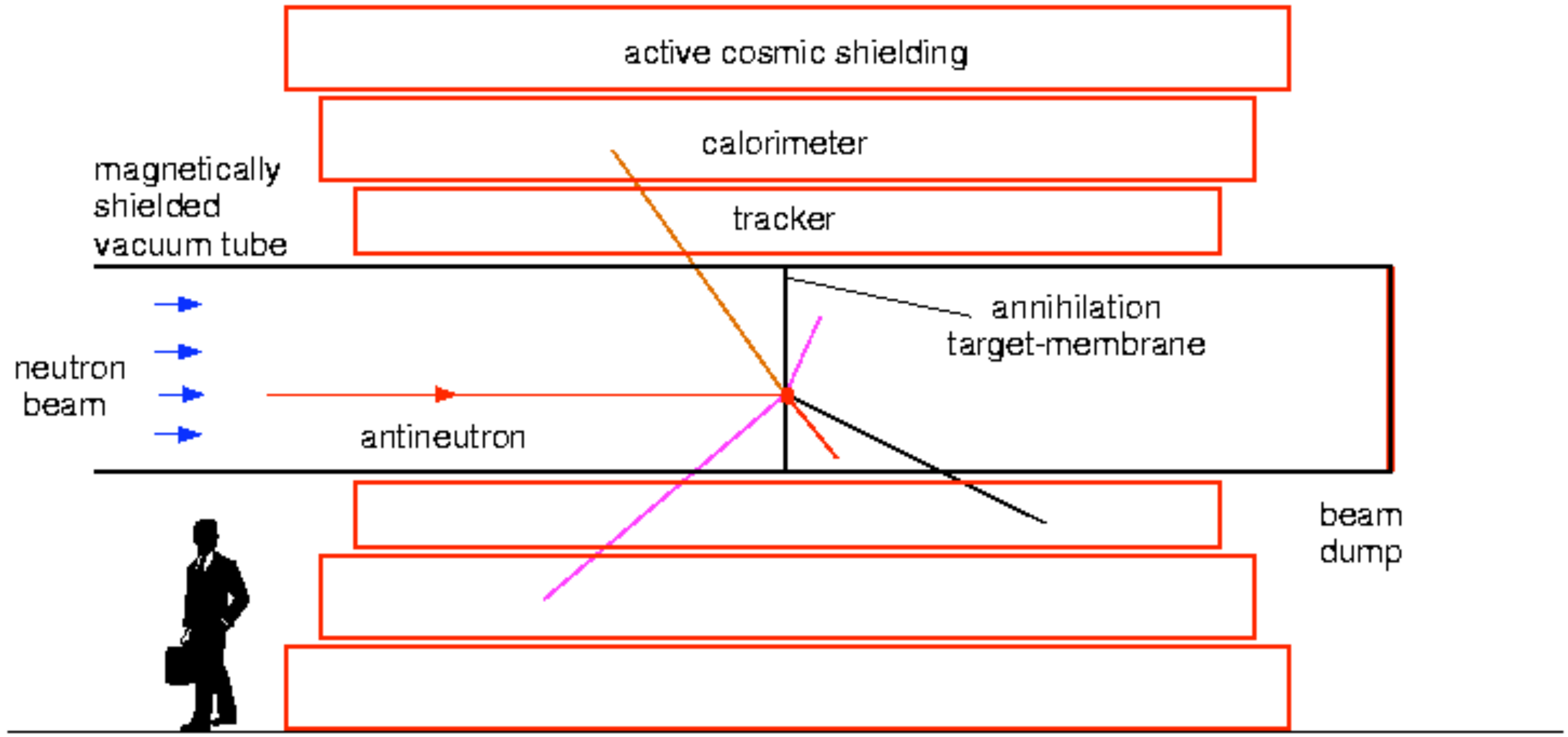
Cold neutrons →

Annihilation detector



Beam stop

The conceptual scheme of antineutron detector



$$\boxed{\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8 \text{ GeV})}$$

Annihilation target: ~100μ thick Carbon film

$\sigma_{\text{annihilation}} \sim 4$ Kb $\sigma_{\text{nC capture}} \sim 4$ mb

vertex precisely defined. No background was observed

Annihilation detector (INFN Padova and Pavia)

1. Inner Vertex Detector: 10 layers of Limited Streamer Tubes (LST), 0.3 g/cm^3, Vertex ±4 cm
2. Outer Calorimeter: 12 layers of LST interleaved with Pb/Al planes
3. Timing: Inner and outer planes of Plastic Scintillators (PSc), 700 ps,
4. Cosmic ray rejection with 95 m^2 outmost layer of PSc, separated by 10 cm Pb.

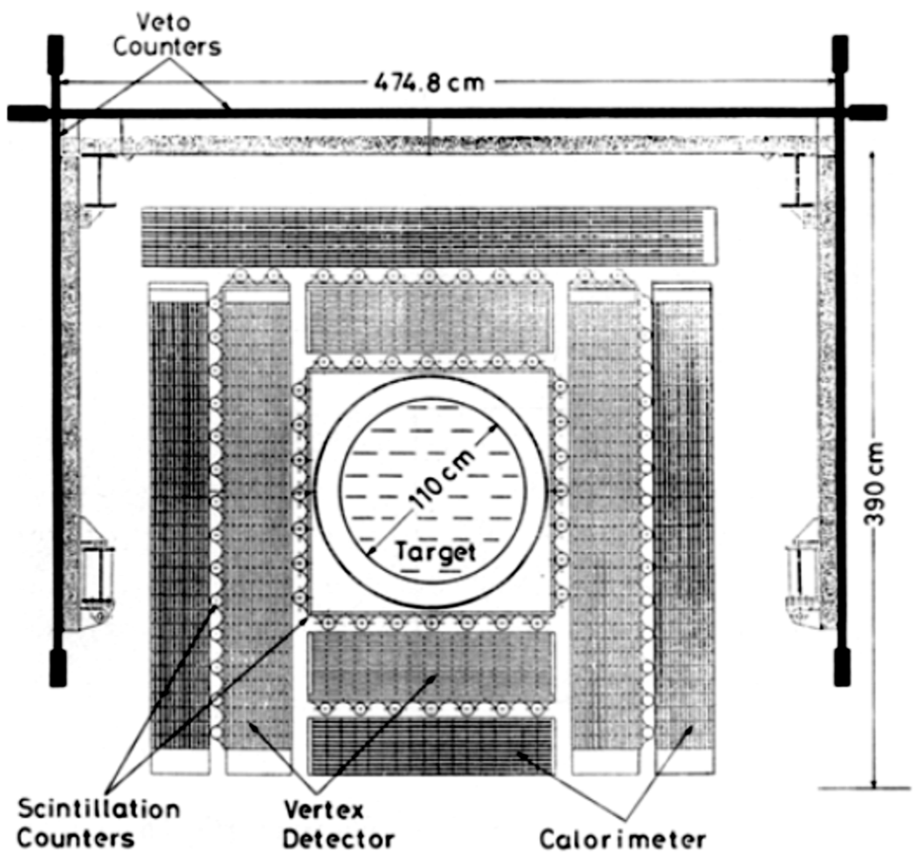


Fig. 5. The $\bar{n}$ annihilation detector (cross sectional view)

60 000 electronic channels
Overall nbar detection efficiency 52±2%.

Explosion-proof gas mixture

Information from D. Dubbers, based on ILL Experiment

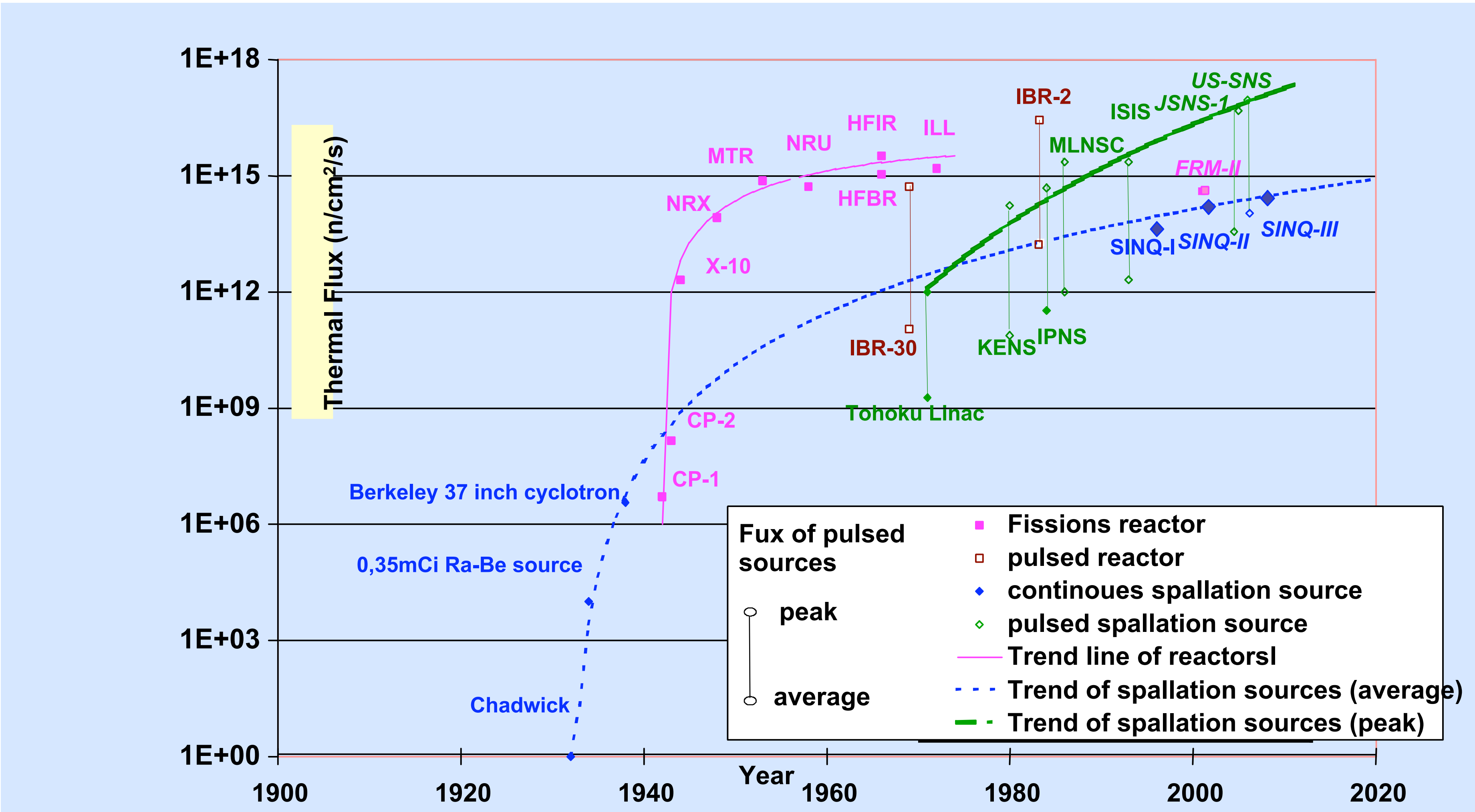
The <10 nT stated limit was conservative. ~1nT should be achievable with a very similar shielding approach. Need to also worry about 60 Hz

Vertex resolution of ILL nnbar detector was very coarse (~5 cm) compared to annihilation target thickness (~100 microns). Lots of room for even further background reduction.

Neutron backgrounds from slow neutron absorption/scattering on annihilation target can be (and needs to be) improved in new experiment to reduce tracker deadtime from MeV capture gammas

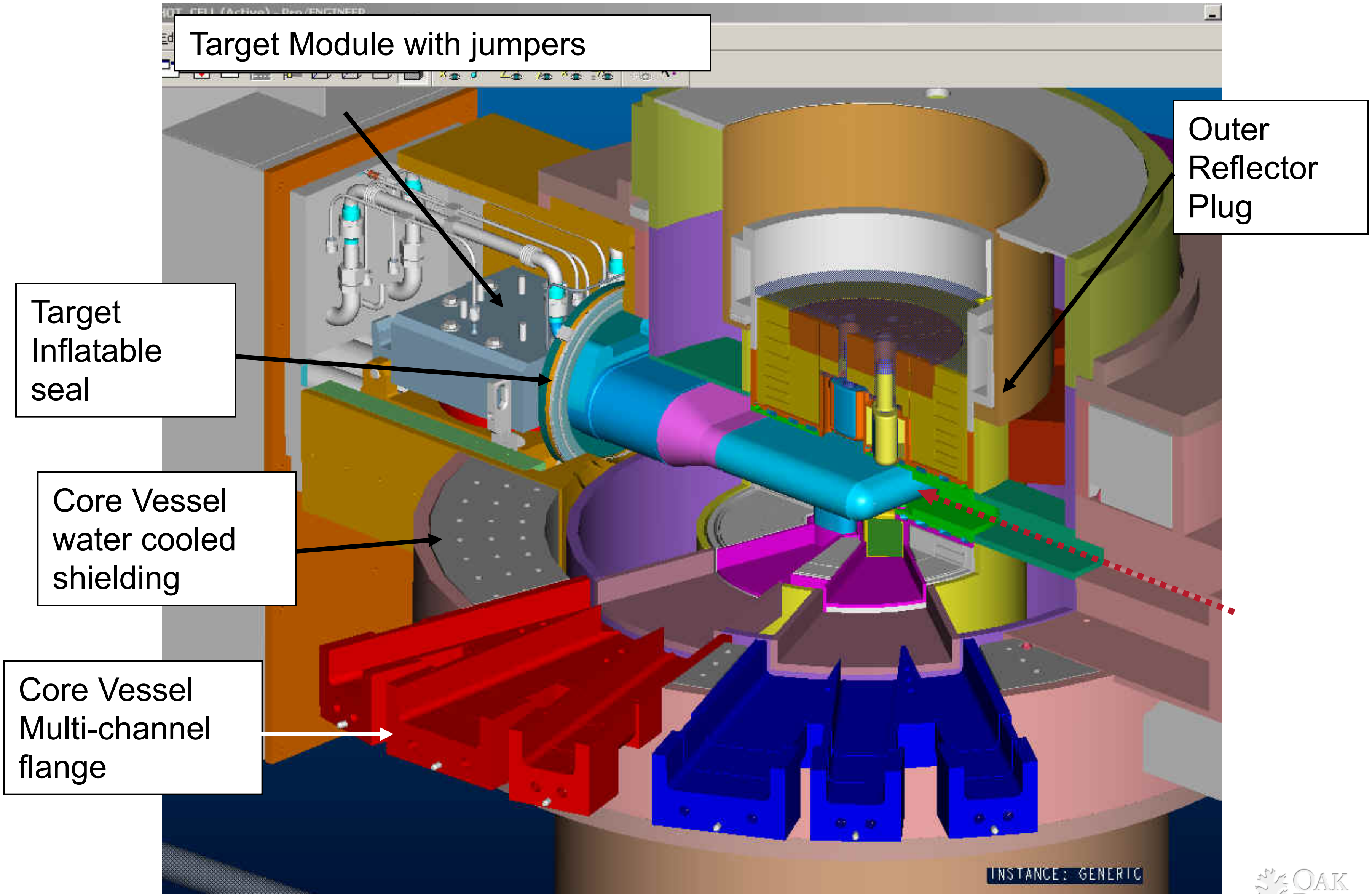
Vacuum chamber/B shielding of experiment still exists at ILL

How to Improve the Experiment? Not so Easy.
Max neutron flux/brightness: ~unchanged for ~4 decades



Neutron flux is increasing only slowly with time R. Eichler, PSI

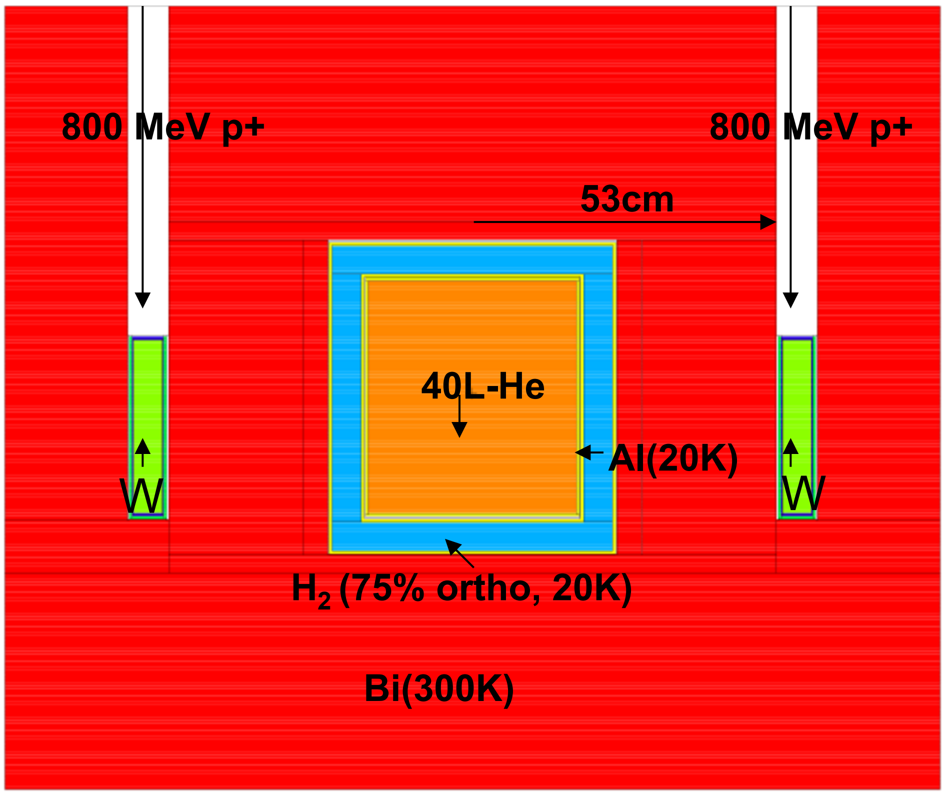
Target Region Within Core Vessel



Summary

- The SNS is operating at a very high level of reliability and at times power levels > 1MW.
- Development of high powered targets based on the SNS experience can be accomplished.
- Cost savings are possible based on the SNS data.
- Experienced personnel are available to help develop these high powered targets.

Inverse cylindrical geometry (1)



$6.6*10^7$ UCN/s/100mA

Heat load @ 100mA ≡ 80KW

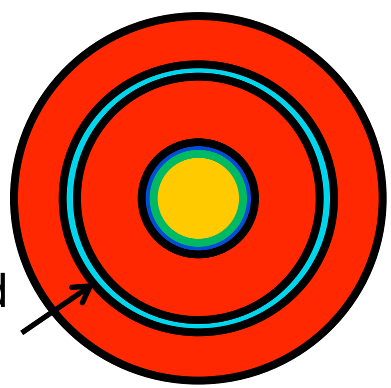
Total heat: 27.4 W

Neutron heat: 17.2 W

Photon heat: 9.6 W

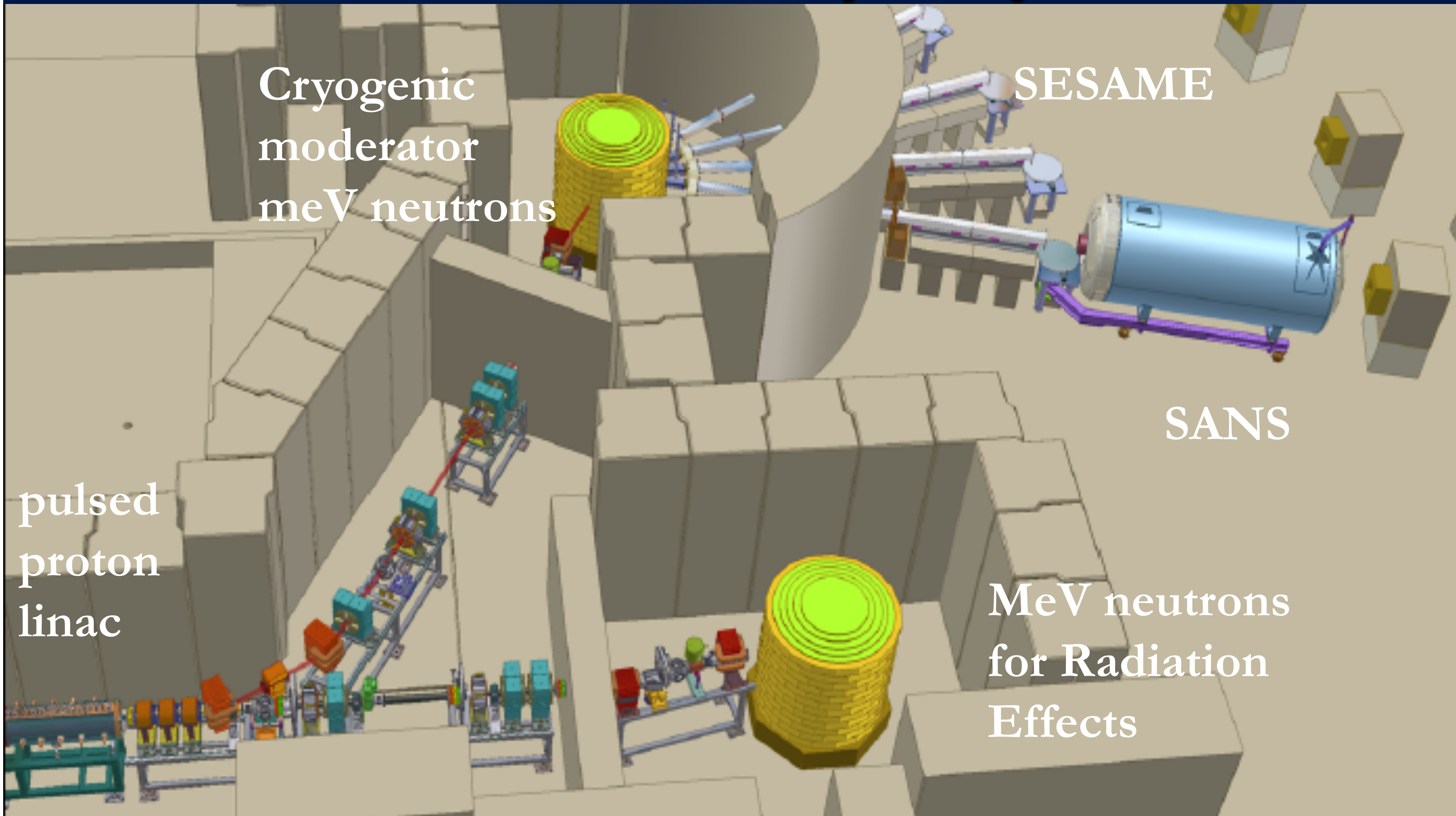
Proton heat: 0.6 W

$2.4*10^8$ UCN/s/100W (heat in the He)



Cylindrical proton target (beam rastered around circumference)

LENS Facility Layout



Designed/built/characterized by graduate students
Local user program in operation

~1MW Slow Neutron Source @Project X?

G. Greene: rough scaling from SNS+ straight guide->~1/4 ILL possible

T. Gabriel: project X source would be less $$$ than SNS, many benefits from SNS experience and ongoing ESS design

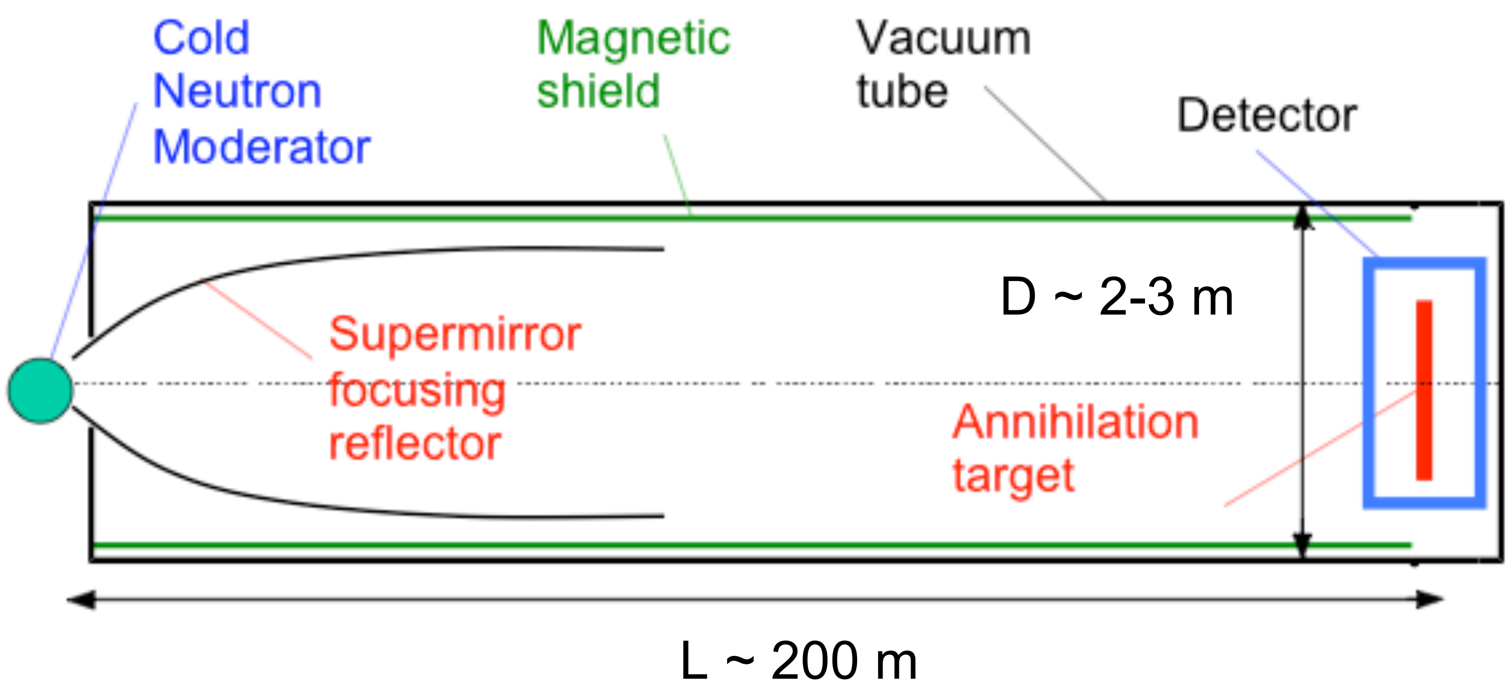
G. Muhrer: MCNP/vetted design for cold source with high kappa superfluid helium exists.

C. Liu (for D. Baxter): LENS neutron source at IU can be used to evaluate cold n moderator improvements (grooved moderators, nanoparticle reflectors,…)

Better Free Neutron Experiment
(Horizontal beam shown: vertical possible)

need slow neutrons from high flux source, access of neutron focusing reflector to cold source, free flight path of ~200m

Improvement on ILL experiment by factor of ~1000 in transition probability is possible with existing n optics technology (see G. Greene talk)



Possible improvements in sensitivity (Nt^2)

•Intrinsic source brightness (assume 1MW)	x 1/4
•Colder moderator (gain goes as λ^2)	x 2
•Coupling to experiment	x 2
•Larger moderator face ($30x30cm^2$ vs $6x12cm^2$)	x 12
•Use "high-m" neutron reflector (assume m=6)	x 36
• Longer experiment (200m vs 76m gain ~ L^2)	x 7

Estimated Sensitivity Gain ~$3x10^3$

Take away message: A substantial improvement is possible with only straightforward extension of existing technology

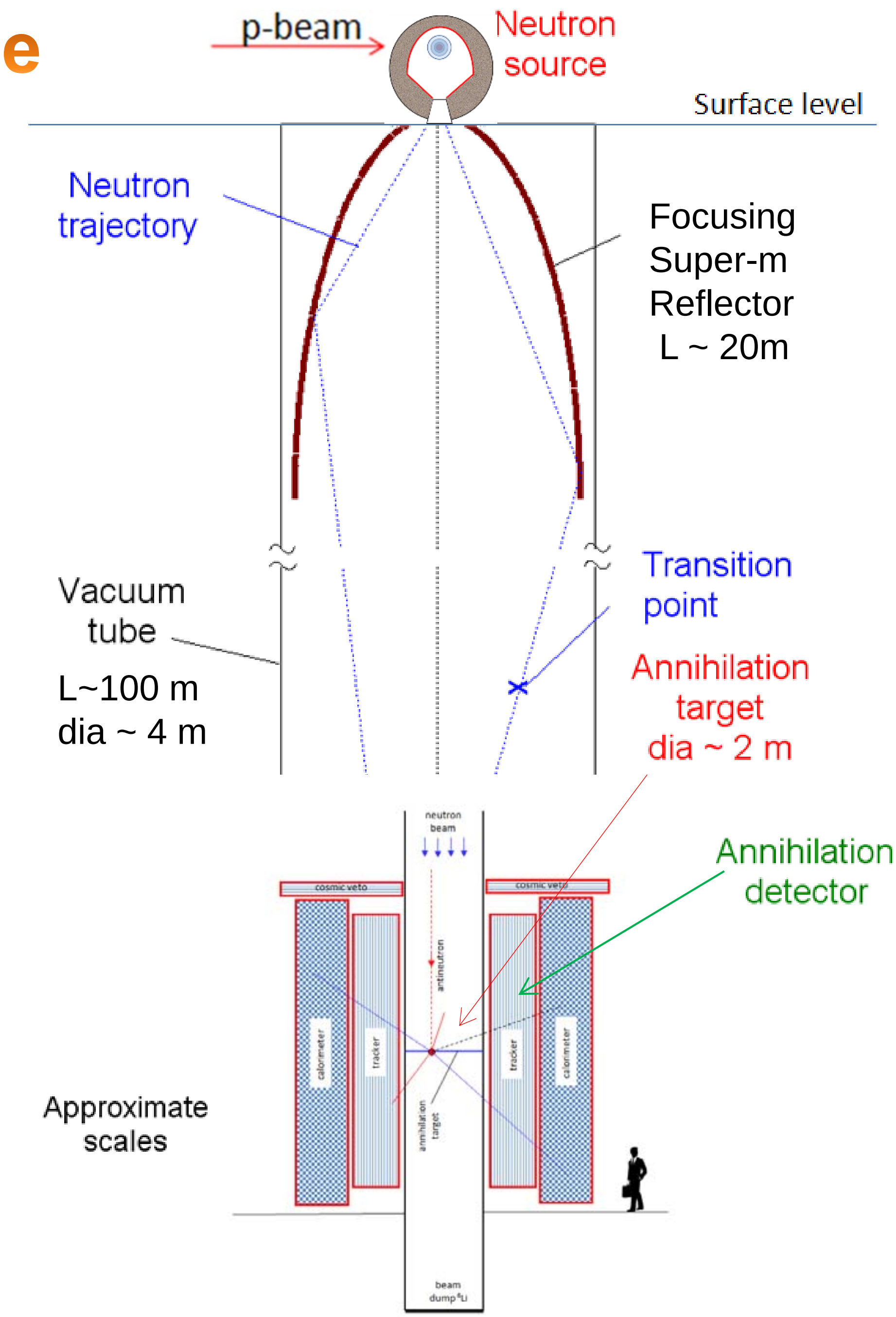
Top-Down vertical scheme

- Can combine most of improvements;
- CW or pulsed;
- Max UCN (<10 m/s) enrichment will be most advantageous;
- Cold and VCN are also used;
- Ultimate combination of all improvements should boost the sensitivity by factor > 1,000 u times several years of operation

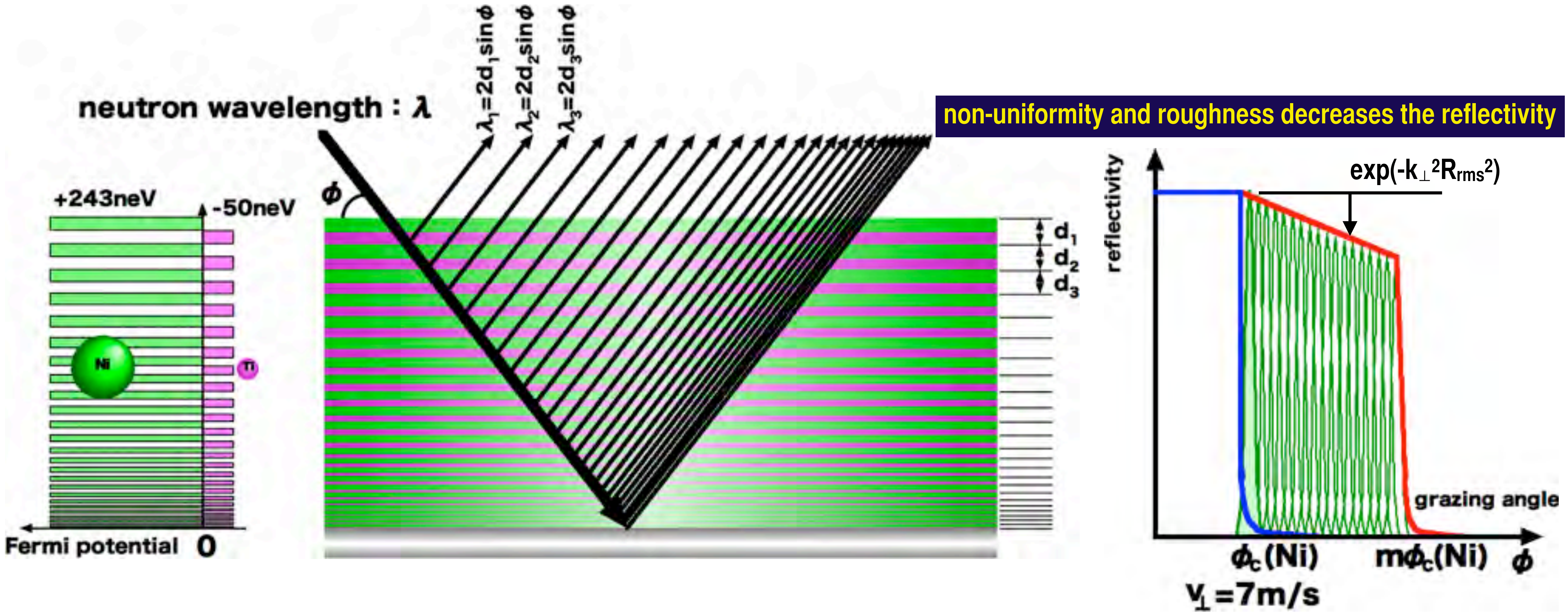
$$h = v_0 t + \tfrac{1}{2} g t^2$$

$$105\ \mathrm{m} = 100\ \mathrm{m/s} \cdot 1\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 1^2\ \mathrm{s}^2$$

$$105\ \mathrm{m} = 10\ \mathrm{m/s} \cdot 3.7\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 3.7^2\ \mathrm{s}^2$$



Supermirror



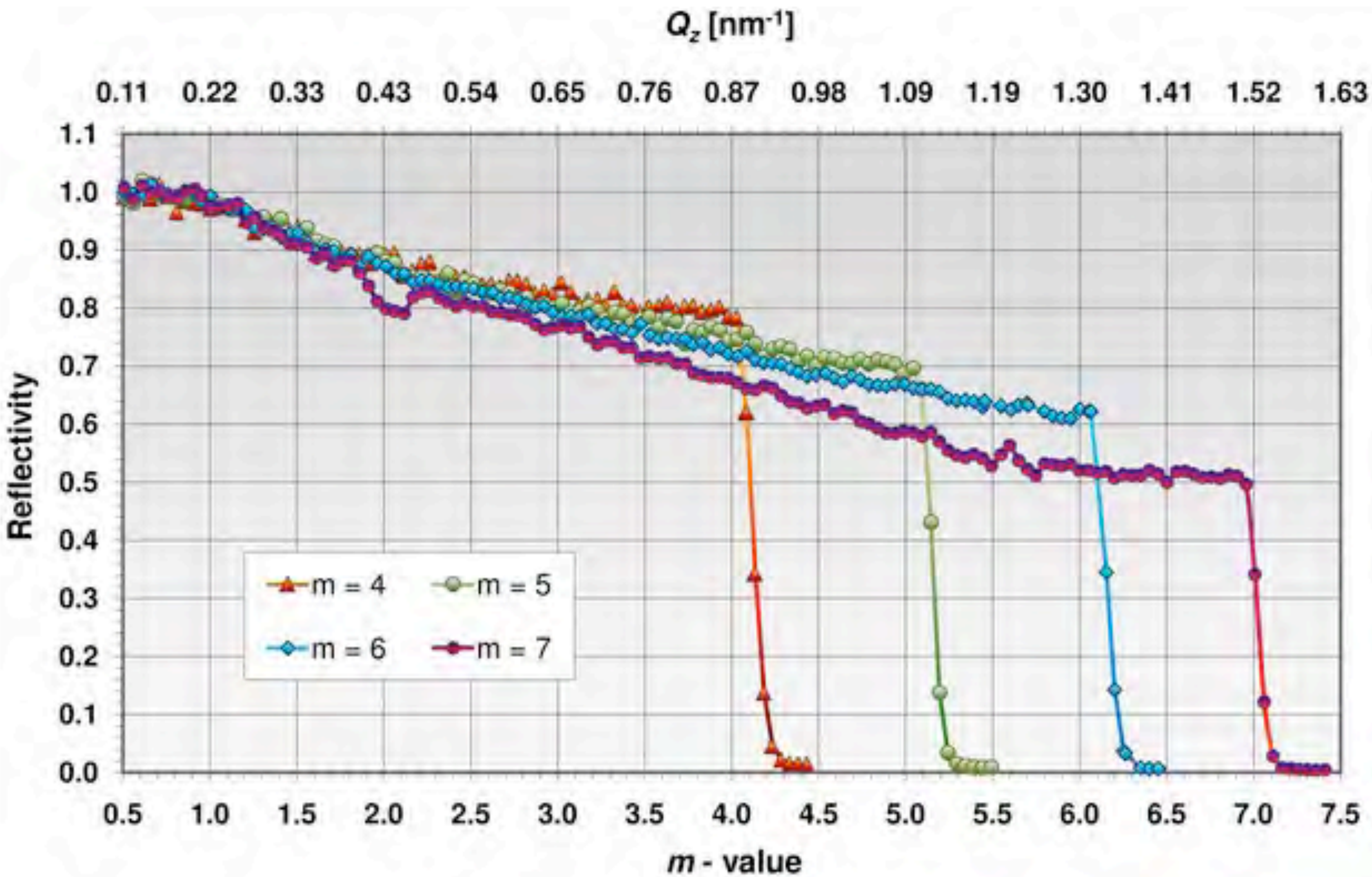
$m = \phi_c / \phi_c(Ni) = v_c(Ni) / v_c$

$\phi_c(Ni)/\lambda = 1.7$ mrad/Å
$v_\perp(Ni) = 7$ m/s

m=4-7 Supermirrors

http://www.swissneutronics.ch/

Supermirror: commercially available up to m=7 (v⊥=50m/s)



Summary

Multilayer mirrors enhances the figure-of-merit of n-nbar experiments.

Multilayer fabrication technology was remarkably improved in the past decade.

monochromatic reflectors m≤10

Focusing of cold neutrons in vertical flight path

supermirrors m≤7

Confinement of VCN
Enhancement of VCN intensity

substrateless supermirrors m≤5

Enhancement of VCN intensity

Supermirror Optics

G. Greene: greatest single contributor to possibility of improved free neutron experiment

H. Shimizu: m=10 mulitlayer n momochromators exist, m=7 n supermirrors, exist, radiation damage can be handled using SM coating on metal, research on H and D-doped diamond-like carbon mirrors in progress

H. Shimizu: Nagoya U active x-ray mirror manufacturing group exists, available ~2015 for new project

Groups in India

- During May, 2011, a short workshop was organized by Dr. Amlan Ray in VECC, Kolkata on N-Nbar oscillation studies
- Several experts from USA participated in this event
- A group from VECC (Kolkata) led by Dr. Ray had a few discussions with the Nuclear and Particle physics groups at SINP (Kolkata)
- The 2 institutes jointly show interest in joining an activity on N-Nbar oscillation studies
  - P. Das, A. Ray, A.K. Sikdar at VECC
  - S. Banerjee, S. Bhattacharya, S. Chattopadhyay at SINP

Free neutron nnbar search: relation with other project X ideas?

Technical:

B. Filippone: both nnbar and (one version of) nEDM can use bright slow neutron source: might one source feed both?

(someone in tracker session): detectors for mu2e experiment and kaon experiments share neutron-induced background issues with nnbar detector

Scientific:

Nnbar improvements squeeze post-sphaeleron baryogenesis. EDM experiments squeeze sphaeleron+EW-scale BSM physics. Do null measurements in both areas at Project X/elsewhere leave leptogenesis by default as the last viable baryogenesis mechanism?

3 Questions

1. ***How much better well could we do at Project X?***
   MUCH BETTER... BUT NEED DETAILED SIMULATIONS

2. ***What would it cost?***
   NEED PRELIMINARY ENGINEERING

3. ***Is it worth doing?***
   NEED ANSWERS TO 1.& 2. PLUS THEORY

NNbar and Project X: What do we need (what will we have?) by Snowmass?

Theory:

sharper understanding of nnbar in nuclei
EFT analysis of all $\Delta B=2$ operators involving standard model fields
(preliminary) lattice calculations of nnbar matrix element

Experiment (underground detectors):

Calculation of $\Delta B=2$ reach for underground liquid Ar detectors

Experiment (free neutrons):

Sensitivity/$$$ ratios for likely options

NNbar Summary

New physics beyond the SM can be discovered by NNbar search

Improvement in free neutron oscillation probability of a factor of ~1,000 is possible

If discovered:

- $n \rightarrow$nbar observation would violate B-L by 2 units, establish a new force of nature, illuminate beyond SM physics, and may help to understand matter-antimatter asymmetry of universe

If NOT discovered:

- will set a new limit on the stability of "normal" matter via antimatter transformation channel. Will constrain some scenarios for B-L violation and "post-sphaeleron" baryogenesis

Summary

New physics beyond the Standard Model can be discovered by NNbar search

Experiments with free neutrons possess very low backgrounds (sharp vertex localization): ILL experiment observed no background. Interpretation of result is independent of nuclear models. Any positive observation can be turned off experimentally with the application of a small magnetic field.

Sensitivity of free neutron experiment for NNbar transition rate can be improved by factor of ~1000 using existing technology [Combination of improvements in neutron optics technology, longer observation time, and larger-scale experiment]. Further improvements in a free neutron experiment can comes from neutron optics technology development.

US high-energy intensity frontier complex could in principle provide the type of dedicated source of slow neutrons needed for NNbar experiment.